

# Cosmic Tau Neutrinos\*

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The collisions between accelerated protons and the photons present in cosmos can be a main source of high-energy neutrinos ( $E \geq 10^6$  GeV) of all flavors above the atmospheric neutrino background. I discuss here the possibility of photohadronic production of high-energy cosmic tau neutrinos in an astrophysical site and study some of the effects of vacuum neutrino flavor mixing on their subsequent propagation. I also discuss the prospects for observations of these high-energy cosmic tau neutrinos in new large neutrino telescopes.

## I. INTRODUCTION

High-energy neutrino ( $E \geq 10^6$  GeV) astroparticle physics is now a rapidly developing field impelled by the need for improved flux estimates as well as a good understanding of detector capabilities for all neutrino flavors, particularly in light of recently growing experimental support for flavor oscillations [1].

Currently envisaged sources of high-energy cosmic neutrinos include, for instance, cores of Active Galactic Nuclei (AGNs) [2,3]. Production of high-energy cosmic neutrinos other than the AGNs may also be possible [4].

In near future, it may become feasible to distinguish between different cosmic neutrino flavors using the information about their event topologies as well as the angle and energy resolutions from several of the large neutrino telescopes and/or (horizontal) shower arrays possibly with a combination of different detection techniques [5].

This contribution is organized as follows: In section II, I briefly discuss the possibility of photohadronic production of cosmic tau neutrinos relative to electron/muon neutrinos, consider some of the effects of vacuum neutrino flavor mixing on their subsequent propagation and discuss some prospects for their observations. In section III, I summarize the discussion.

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\*Talk given at YITP Workshop on Theoretical Problems related to Neutrino Oscillations, 28 February-01 March, 2000, Kyoto, Japan.

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## II. COSMIC TAU NEUTRINOS

### A. Some flux estimates

I consider here briefly the photohadronic ( $\gamma p$ ) production of high-energy cosmic tau neutrinos in AGNs only. In  $\gamma p$  collisions, the cosmic tau neutrinos (and anti neutrinos) are mainly produced from the relevant decay chain of  $D_S^\pm$  in  $\gamma p \rightarrow D_S^\pm + X$ . Following the notation of Ref. [6], the cosmic tau neutrino flux spectrum can be calculated in roughly three steps. The first step in estimating the cosmic tau neutrino flux spectrum is to calculate the yield of the relevant unstable hadron ( $D_S^\pm$ ) in  $\gamma p$  collisions:

$$Y_{D_S^\pm} = \int \int \int dE_p dE_\gamma d\cos\theta (1 - \cos\theta) \frac{n_p(E_p)}{n_p(E_{D_S^\pm})} \frac{1}{\sigma} \frac{d\sigma}{dE_{D_S^\pm}} \frac{n_\gamma(E_\gamma)}{n_0}, \quad (1)$$

where  $\theta$  is the angle between photon and proton momentum in the laboratory system. The yield in Eq. (1) is essentially a result of folding the given photon spectrum,  $n_\gamma(E_\gamma)/n_0$  having energy  $E_\gamma$  with the proton spectrum having a power law,  $n_p(E_p) \sim E_p^{-(\epsilon+1)}$  ( $\epsilon \geq 1$ ) while taking into account the details of relevant kinematics. The differential cross-section can be taken from, for instance, from [7], whereas  $n_\gamma(E_\gamma)/n_0$  is taken from [2]. The second step is to convolve this yield with the relevant decay functions of  $D_S^\pm$  to obtain the cosmic tau neutrino yield. This yield is further convolved with the proton spectrum to obtain the cosmic tau neutrino flux. Finally, the cumulative cosmic tau neutrino flux spectrum is obtained by integrating the cosmic tau neutrino flux over the luminosity function of the AGN while restoring the relevant numerical factors. A notable characteristic feature in the shape of the (cumulative) neutrino flux spectrum as a function of neutrino energy is the flat region for relatively small neutrino energies because of kinematics and subsequently a steeply falling flux spectrum with roughly the same spectral index as that for protons for relatively large neutrino energies, with rather smooth interpolation between these two asymptotic behaviours. The principal difference between the tau and non tau (electron and muon) neutrino flux spectra is that of relatively lower value of the former as compared to latter with overall the same flux spectrum shape. The main reasons being:  $\sigma_{\gamma p \rightarrow DX}/\sigma_{\gamma p \rightarrow \pi X} \leq \mathcal{O}(10^{-3} - 10^{-4})$  and secondly  $\text{BR}(D \rightarrow \nu_\tau)/\text{BR}(\pi \rightarrow \nu_\mu) \leq 3/99 \sim \mathcal{O}(10^{-2})$ . Therefore, the total relative suppression is  $\sim \mathcal{O}(10^{-4} - 10^{-5})$  essentially for all relevant center of mass energies. It is relevant to mention that there is no formation of resonance in  $\gamma p \rightarrow D_S^\pm + X$  channel unlike in  $\gamma p \rightarrow \pi^\pm + X$  channel for the relevant center of mass energies.

### B. Effects of vacuum neutrino flavor mixing

It has been pointed out that there are no matter effects on vacuum neutrino flavor oscillations for relevant  $\delta m^2$  values [ $\mathcal{O}(10^{-10}) \leq \delta m^2/\text{eV}^2 \leq \mathcal{O}(1)$ ] for high-energy cosmic

neutrinos originating from AGNs [8]. I, therefore consider here the effects of vacuum neutrino flavor mixing/oscillations only. For some other possible mixing effects, see [9].

The effects of vacuum neutrino flavor mixing in the context of three flavors are analytically discussed in [10]. It was pointed out there that starting from the ratio of intrinsic cosmic neutrino fluxes as  $F_e^0 : F_\mu^0 : F_\tau^0 = 1 : 2 : 0^1$ , irrespective of the flavor oscillation solution to the solar electron neutrino deficit, one obtains the ratio of final (downward going) cosmic neutrino fluxes as  $F_e : F_\mu : F_\tau = 1 : 1 : 1$ . A somewhat detailed numerical study that properly incorporates the effects of non vanishing  $\theta_{13}$  and the CP violating phase  $\delta$  confirms that indeed this is the case, i.e., the normalized difference between any two neutrino flavors,  $\Delta F_{\alpha\beta}$  ( $\alpha \neq \beta$ ;  $\alpha, \beta = e, \mu, \tau$ ) is typically of the order of 1% [11]:

$$\Delta F_{\alpha\beta} = \frac{|F_\alpha - F_\beta|}{\sum_\alpha F_\alpha} \leq \mathcal{O}(10^{-2}). \quad (2)$$

An empirical determination of  $\Delta F_{\alpha\beta}$ , if become feasible, may be useful to test the unconventional astrophysics/particle physics.

Here, I consider the possibility that these three active light neutrinos mix with a fourth (sterile) flavor. This possibility accommodates the flavor oscillation solution for LSND anomaly [12] in addition to explaining the solar electron and atmospheric muon neutrino deficits also in terms of flavor oscillations with the introduction of a new  $\delta m^2$  scale [ $\delta m^2 \sim \mathcal{O}(1) \text{ eV}^2$ ] relative to three flavor mixing scheme. If the effective number of light neutrino flavors from the Big-Bang nucleosynthesis is less than four then four ( $\theta_{13}, \theta_{14}, \theta_{23}, \theta_{34}$ ) out of six mixing angles are small and can be neglected [13,14]. Following the description given in Ref. [10] and using the parameterization for the  $4 \times 4$  neutrino mixing matrix from Ref. [13], one obtains the following  $P$  matrix for vanishing  $\delta$ 's:

$$P = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1/2 & 1/2 & 0 \\ 0 & 1/2 & 1/2 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \quad (3)$$

Note that except the last row and column, this  $P$  matrix is the same as that for SMA(MSW) situation in the context of three flavors. The absence of a relatively dense object is assumed here between the cosmologically distant AGNs ( $\sim 100 \text{ Mpc}$ , where  $1 \text{ pc} \sim 3 \times 10^{18} \text{ cm}$ ) and the neutrino telescopes so as not to change this (vacuum) flavor oscillations pattern significantly. Also note that the neutrino energy dependence in relevant (vacuum) flavor

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<sup>1</sup>As discussed in previous subsection,  $F_\tau^0$  is negligibly small and therefore can be taken as 0.

oscillation probability expression is averaged out here for the entire neutrino energy range relevant for observations. Thus, starting from  $F_e^0 : F_\mu^0 : F_\tau^0 : F_s^0 = 1 : 2 : 0 : 0$ , one obtains  $F_e : F_\mu : F_\tau : F_s = 1 : 1 : 1 : 0$  at the level of  $F_e^0$ . That is, in this (mass and) mixing scheme one also obtains a (downward going) cosmic tau neutrino flux comparable to corresponding cosmic non tau neutrino flux.

### C. Prospects for observations

Currently, two suggestions are available to identify the cosmic tau neutrino flavor. Both suggestions are based on the relatively short decay lifetime of the  $\tau$  lepton produced in deep inelastic scattering of cosmic tau neutrinos with the nuclei.

There is a suggestion of measuring cosmic tau neutrino flux through double shower (*double bang*) events in underwater/ice Cerenkov telescopes [15]. A more recent suggestion is to detect a small pile up of upward going  $\mu$ -like events in the ( $10^4$ - $10^5$ ) GeV energy range with a fairly flat zenith angle dependence [16].

Using the flux estimates given in [2], the cosmic tau neutrino induced downward going double shower event rate for a typical  $\text{km}^2$  surface area neutrino telescope in ice/water can be  $\sim \mathcal{O}(1)/\text{yr}\cdot\text{sr}$  using Eq. (3) for  $E \geq 10^6$  GeV.

It may also become possible to obtain some useful information about the cosmic neutrino flavor from large (horizontal) shower arrays [17]. For instance, the criterias of separableness and containedness of the two cosmic tau neutrino induced showers as discussed in [10,15] implies that for the Pierre Auger array, the following essentially half an order of magnitude neutrino energy interval may be relevant:  $5 \times 10^8 \leq E/\text{GeV} \leq 10^9$ . Note that the two showers develop here mainly in air. However, the energy at which the two showers start separating in Pierre Auger lies below the planned threshold for detection in Pierre Auger so that even in the case of the most favourable cosmic neutrino flux and oscillation probabilities, the expected number of events per year turns out to be small.

## III. CONCLUSIONS

Irrespective of neutrino flavors, in each of the neutrino (mass and) mixing scheme discussed here, the final flux of downward going high-energy cosmic tau neutrinos is essentially comparable to that of non tau neutrinos, whereas intrinsically it is negligible.

Prospective observation of cosmic tau neutrino flavor may become feasible in new large neutrino telescopes or/and in (horizontal) shower arrays.

*Acknowledgments.* This work is supported by a Japan Society for the Promotion of Science fellowship. The author thanks O. Yasuda for comments.

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